NASA-CR-202733

Planet. Space Sci., Vol. 40, No. 5, pp. 663-670, 1992
Printed in Great Britain

0032-0633/92 $5.00+0.00
Pergamon Press Ltd

THE TEMPORAL EVOLUTION OF THE IONOSPHERIC SIGNATURES OF SUBAURORAL ION DRIFTS

R. J. MOFFETT
Department of Applied and Computational Mathematics, University of Sheffield, P.O. Box 597, Sheffield S10 2UN, U.K.

R. A. HEELIS
Center for Space Sciences, University of Texas at Dallas, Box 830688, Richardson, TX 75083, U.S.A.

and

R. SELLEK and G. J. BAILEY
Department of Applied and Computational Mathematics, University of Sheffield, P.O. Box 597, Sheffield S10 2UN, U.K.

(*Received in final form* 10 *December* 1991)

Abstract—A model of the ionosphere and plasmasphere is used to investigate the effects of an imposed westward plasma drift on O^+ and molecular ion behaviour in the nightside ionosphere. A closed subauroral tube of plasma is considered and the velocity input persists for 30 min. The rapid increase in the F-region ion temperature resulting from ion–neutral frictional heating causes an immediate surge in the O^+ field-aligned velocity, upwards in the topside ionosphere and downwards below the $F2$-peak, but after about 10 min into the event the surge in the topside disappears. After the event there is a return flow of O^+ from the plasmasphere. The relative abundance of O^+ decreases during the event due to the increased rate of conversion of O^+ into NO^+ and O_2^+; the decrease is more marked for greater values of the imposed westward ion drift. At a given F-region altitude, a low relative abundance of O^+ is more likely under sunspot maximum atmospheric conditions. There are also significant percentages of NO^+ in the topside ionosphere during the event. The bearing of these results on satellite observations of SAID (subauroral ion drift events) and on EISCAT incoherent scatter radar observations of ion heating events is discussed.

1. INTRODUCTION

In a recent paper, Anderson *et al.* (1991) have presented the results of observations of subauroral ion drift events (SAID) made on the *Atmosphere Explorer-C* and *Dynamics Explorer* 2 spacecraft. The results were used to examine the temporal evolution of SAID and to determine the effects of SAID on F-region ion composition and on the mid-latitude F-region trough.

The results of Anderson *et al.* (1991) indicate that SAID events may last longer than 30 min (and less than 3 h). This has implications for the modelling of such events. Previous calculations of the effect of a SAID on the plasma contained in a single plasmaspheric magnetic flux tube (Sellek *et al.*, 1991, 1992; Moffett *et al.*, 1991) have been limited to what have been termed "spikes" of enhanced westward flow, i.e. the westward flow was imposed for 10 min and then switched off. Some of the immediate signatures of the SAID in the ionosphere (such as the ion temperature enhancement in the F-region) may persist almost unchanged throughout a SAID of duration 30 min but others, such as the behaviour of the molecular ions and the fluxes of atomic ions in the topside ionosphere, may evolve with time. The presence of large ion drifts perpendicular to the magnetic field (and the presence of molecular ions, even at altitudes as high as 600 km) presents a significant challenge to the interpretation of the retarding potential analyzer data. The measured distribution functions are non-Maxwellian and while the fitting procedures can accommodate such distributions (St-Maurice *et al.*, 1976) care should be exercised in interpreting the "temperature" as the width of a Maxwellian distribution. When a Maxwellian distribution is assumed, the temperature still indicates the width of the distribution function but no information about the shape of the function is available.

In this paper the model of Sellek *et al.* (1991) is used to investigate the effects of a SAID that persists for 30 min. The approach of the behaviour of the topside ionosphere to steady state is examined. Emphasis is also placed on the details of the ion composition in the F-region, in view of the recent experimental results on ion composition (Anderson *et al.*, 1991) and in view of the limited results on this topic presented in earlier model papers.

The bearing of the ion composition results on the interpretation of incoherent scatter radar results is also discussed. Observations made by using, for example, the European incoherent scatter radar facility (EISCAT) have revealed the occurrence of what have been termed "ion heating events". The ion heating, as in SAID, can arise from large electric fields causing rapid plasma motions and thus ion–neutral frictional heating. In connection with their relationship to ion density troughs Rodger *et al.* (1992) have noted the likely locations of such large electric fields.

2. MODEL CALCULATIONS AND INPUTS

The mathematical model of the Earth's ionosphere and plasmasphere used in this study is described in detail by Bailey and Sellek (1990). In the model, values of the concentrations, temperatures and field-aligned velocities of the O^+, H^+, He^+, N_2^+, O_2^+ and NO^+ ions, and the electrons, are obtained from time-dependent equations describing the chemical and physical processes controlling the thermal plasma. These equations, for the continuity, momentum and energy balance of the plasma confined within closed magnetic flux tubes, are solved along the axis of a flux tube connecting the conjugate hemispheres. A centred axial-dipole representation of the geomagnetic field is assumed and for the present study all calculations were performed for the $L = 4$ field line which intersects the Earth's surface near 60° latitude. For the model calculations, equinox (day 82) conditions were chosen and, to provide results representing both solar minimum and maximum, $F_{10.7}$ fluxes of 80×10^{-22} and 190×10^{-22} W m^{-2} Hz^{-1}, respectively, were used. An A_p index value of 20 was chosen to simulate thermospheric conditions for moderate magnetic activity.

The model results presented in Section 3 have been obtained from a common base set of calculations commencing at 12:00 L.T. and running for 3.5 consecutive 24-hour periods. These calculations yield data for a magnetic flux tube located at local midnight and simulating an early stage of ion replenishment following depletion of the outer plasmasphere by a magnetic storm. Using these data as input, four additional sets of calculations were performed for one further hour of elapsed time. The first set of calculations represents a straightforward continuation of the base calculations with no applied westward $E \times B$ drift. For the second, third and fourth sets, however, the magnetic flux tube was subjected to sudden westward drifts with velocities of 2, 3 and 4 km s^{-1}, respectively, at an elapsed time of 5 min after midnight. These drifts persist for 30 min in elapsed time before decreasing rapidly back to zero. In each case, the local time was held fixed at 24:00 since otherwise the flux tube would move back into the daylight sector when under the influence of applied westward drifts of 3 and 4 km s^{-1}. This is not to imply that daytime SAID events are not observed (see, for example, Pinnock, 1985) but is a computational simplification to avoid plasma temperature increases caused by incident solar radiation.

3. RESULTS AND DISCUSSION OF THEIR RELEVANCE TO SAID

Sunspot maximum conditions

The primary ionospheric signature of the SAID (Anderson *et al.*, 1991) is illustrated by the ion temperature profiles shown in Fig. 1: these results were obtained for an ion drift of 2 km s^{-1}. At F-region altitudes the ion temperature, T_i, has increased by over 3000 K from its unperturbed value. The difference $T_i - T_n$, where T_n is the neutral particle temperature, is due to ion–neutral frictional heating and is approximately proportional to the square of the ion drift velocity, $V_\perp^2$, for large values of $V_\perp$, assuming that the neutral air wind velocity is relatively small. The time dependences of T_i at fixed altitudes are shown in Fig. 2. It is seen that at 300 and 500 km altitudes, where ion–neutral friction is the dominant heating mechanism, T_i increases very rapidly when the SAID is applied. At greater altitudes the more tenuous neutral air dramatically reduces the frictional heating. The ion temperatures at these altitudes rise more slowly due to the upwards conduction of heat from the region of frictional heating. These time scales are evident again when the SAID is removed, after 35 min elapsed

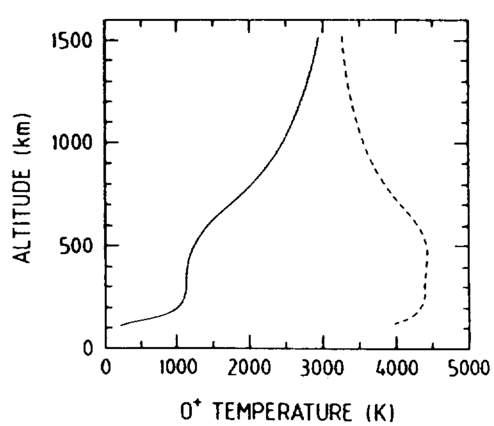

FIG. 1. CALCULATED O^+ TEMPERATURE AS A FUNCTION OF ALTITUDE AT ELAPSED TIME 20 min FOR SUNSPOT MAXIMUM CONDITIONS: ——, NO WESTWARD DRIFT; - - - -, WESTWARD DRIFT VELOCITY 2 km s^{-1}.

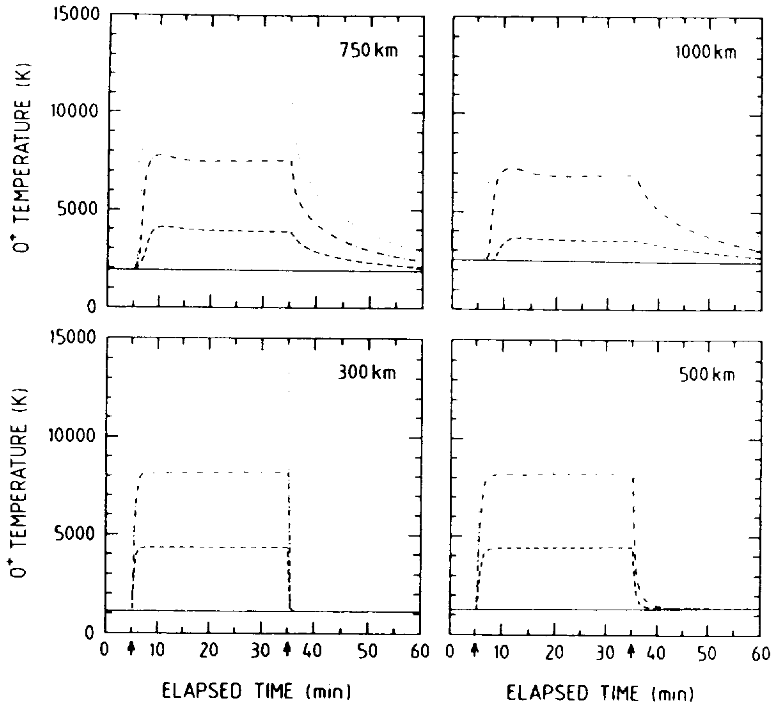

FIG. 2. CALCULATED O^+ TEMPERATURE AT FOUR ALTITUDES AS A FUNCTION OF ELAPSED TIME FOR SUNSPOT MAXIMUM CONDITIONS: WESTWARD DRIFT VELOCITY: ——, ZERO; – – –, 2 km s^{-1}; - - -, 3 km s^{-1}; ·····, 4 km s^{-1}.
The duration of the model SAID event is indicated by the arrows on the time scale.

time. At the lower altitudes, cooling due to ion–neutral heat transfer occurs rapidly, whereas at greater altitudes the heat in the ion gas is first conducted downwards. Note, however, that the time scales for establishing a new equilibrium temperature distribution are shorter than the times required to transport the plasma significant distances.

The rapid increase in T_i in the F-region increases the plasma pressure relative to that in the topside. Rapid upward field-aligned flows are generated (Sellek *et al.*, 1991), in accordance with experiment (Anderson *et al.*, 1991). The development of these flows with time for an ion drift of 2 km s^{-1} is shown in Fig. 3. It is clear that as the plasma pressure distribution approaches steady state (illustrated by the T_i behaviour in Fig. 2) the field-aligned flows in the topside, although remaining upward, subside quite rapidly. When the zonal ion velocity is switched off, O^+ tends to return from the plasmasphere to the F-region. Also apparent is the contrasting behaviour at 300 km altitude. Here, a downward velocity results

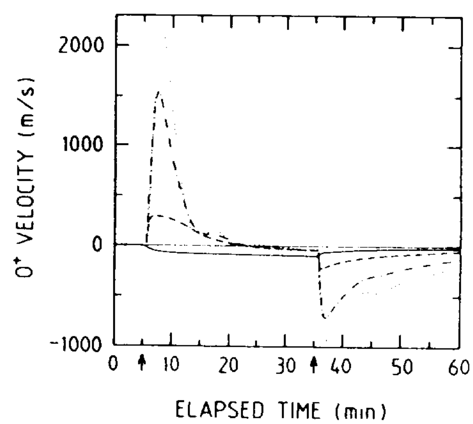

FIG. 3. CALCULATED FIELD-ALIGNED O^+ VELOCITY AS A FUNCTION OF ELAPSED TIME AT FOUR ALTITUDES FOR SUNSPOT MAXIMUM CONDITIONS WITH A WESTWARD DRIFT VELOCITY OF 2 km s^{-1}: ——, 300 km; – – –, 500 km; - - -, 750 km; ·····, 1000 km.
Positive velocities are upward; the duration of the model SAID event is indicated by the arrows on the time scale.

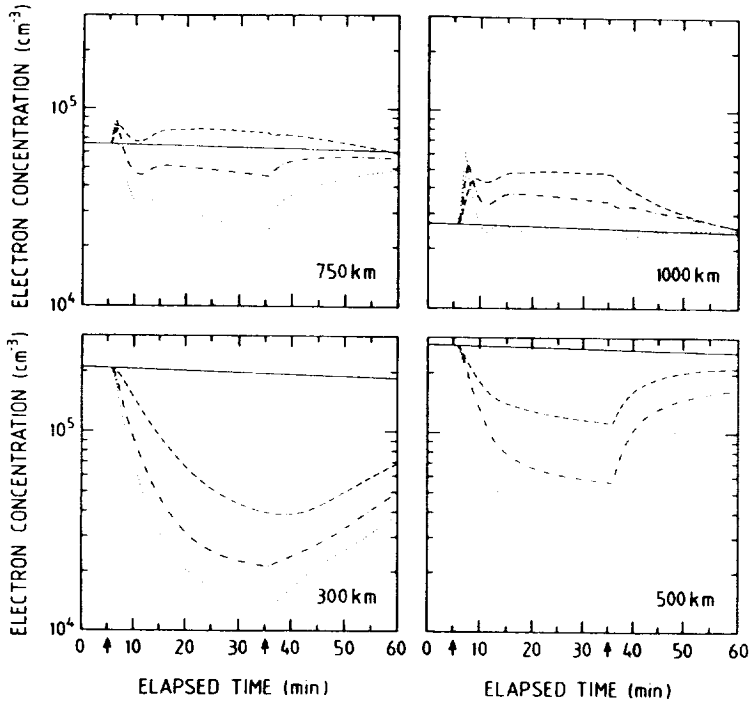

FIG. 4. CALCULATED ELECTRON CONCENTRATION AS A FUNCTION OF ELAPSED TIME AT FOUR ALTITUDES FOR SUNSPOT MAXIMUM CONDITIONS: WESTWARD DRIFT VELOCITY: ——, ZERO; – – –, 2 km s^{-1}; –·–·–, 3 km s^{-1}; ·····, 4 km s^{-1}.
The duration of the model SAID event is indicated by the arrows on the time scale.

from plasma expansion below the *F*-peak (peak height is 385 km before the event) and from enhanced loss of plasma associated with the large drift velocity.

The behaviours of the electron and ion concentrations [Figs 4 and 5(a)] depend on the interaction of chemical and dynamical effects. The rate of conversion of O^+ into NO^+ and O_2^+ depends on the rate coefficients for the reactions

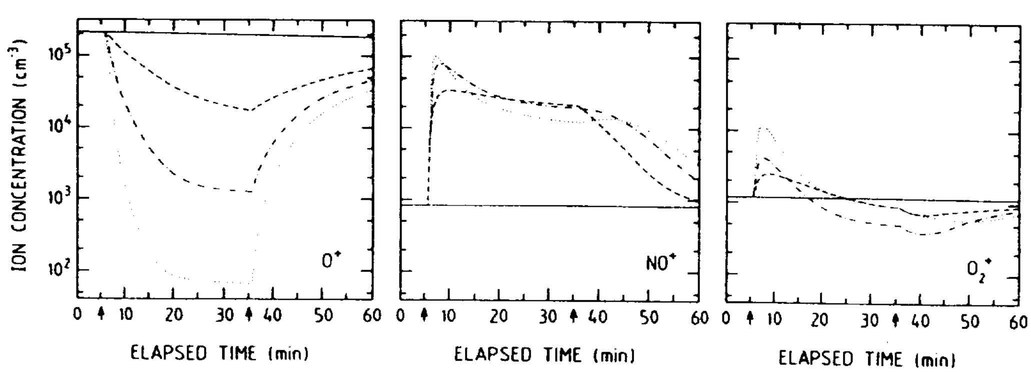

FIG. 5(a). CALCULATED ION CONCENTRATIONS AS A FUNCTION OF ELAPSED TIME AT 300 km ALTITUDE FOR SUNSPOT MAXIMUM CONDITIONS: WESTWARD DRIFT VELOCITY: ——, ZERO; – – –, 2 km s^{-1}; –·–·–, 3 km s^{-1}; ·····, 4 km s^{-1}.
The duration of the model SAID event is indicated by the arrows on the time scale.

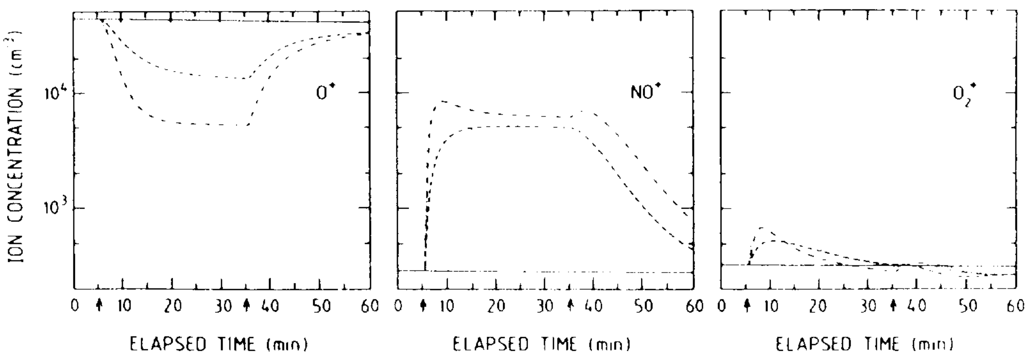

FIG. 5(b) AS FOR FIG. 5(a) EXCEPT THAT THE CONDITIONS ARE APPROPRIATE TO SOLAR MINIMUM.

$$O^+ + N_2 \rightarrow NO^+ + N \quad (1)$$

and

$$O^+ + O_2 \rightarrow O_2^+ + O, \quad (2)$$

and on the densities of the neutral molecular species, N_2 and O_2. The rate coefficients increase rapidly with temperature when T_i is raised significantly above, say, the neutral air temperature (Schunk *et al.*, 1975; Albritton *et al.*, 1977; St-Maurice and Torr, 1978). Note that the fit by St-Maurice and Torr (1978) relies on the cross-sections of Albritton *et al.* (1977) in preference to earlier cross-sections. In the early stages of the event, as T_i increases rapidly in the F-region (where N_2 and O_2 densities are appreciable), conversion of O^+ to NO^+, with O_2^+ playing a minor role, leads to severe reduction in the O^+ density at 300 km altitude and an increase in NO^+ density (Fig. 5); the electron concentration declines at this altitude (Fig. 4). The field-aligned surge of O^+ into the topside ionosphere and plasmasphere also contributes to the reduction in O^+ density (Sellek *et al.*, 1991). The trend of decreasing O^+ and NO^+ densities continues to the end of the event.

Anderson *et al.* (1991) have pointed out that SAID troughs are often embedded in the mid-latitude trough that is presumably formed by the Spiro *et al.* (1978) plasma stagnation mechanism or is due to vibrationally excited N_2 spilling from the auroral zone. The plasma stagnation occurs in the dusk sector when the magnetospheric convection opposes corotation. The model results do not attempt to account for the ambient mid-latitude trough. Nonetheless, the model trough concentrations for the larger ion drifts are comparable (10^4–3×10^4 cm^{-3} at 300 km altitude) to those observed. Also, the model results demonstrate that the trough depth at a particular altitude will depend on the duration of the event.

It has also been pointed out by Anderson *et al.* (1991) that at higher altitudes the trough signature is considerably mitigated or even absent. Figure 4 shows that the degree of mitigation will depend on the altitude considered, on the value of the ion drift velocity and on the duration of the event.

In Fig. 6 are presented ion composition results for various values of the imposed westward ion drift velocity. At 300 km altitude, in the absence of the westward velocity, the ion gas is composed almost completely of O^+. For typical SAID, the percentage O^+ declines rapidly when the westward velocity is switched on and continues to decline with time as more O^+ is destroyed to produce NO^+ and O_2^+. Anderson *et al.* (1991) have presented results from *DE*-2 satellite observations showing that, under March 1982 thermospheric conditions, a SAID with drift of 3 km s^{-1} could give rise to molecular ion dominance around 300 km altitude. The model results for 3 km s^{-1} are consistent with these experimental results, provided the SAID has been operative for at least a few minutes. Figure 6(b) shows that, at a given time during the SAID, the altitude dependence of the percentage O^+ is very marked at altitudes above 250 km. For zero drift, this composition change occurs below 250 km.

Sunspot minimum conditions

Results for T_i, O^+ field-aligned velocity and N_e are not presented for sunspot minimum since the dependences of SAID signatures on time and altitude seen in these variables are qualitatively similar to those for sunspot maximum. Attention is drawn instead to the behaviour of the ion composition at sunspot minimum [Figs 5(b) and 7].

For a given drift, elapsed time and F-region altitude, the percentage O^+ at sunspot minimum (Fig.

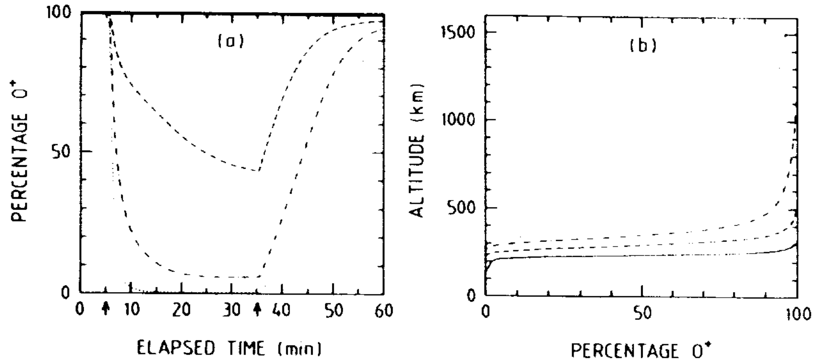

FIG. 6. CALCULATED PERCENTAGE O^+ FOR SUNSPOT MAXIMUM CONDITIONS: IN PANEL (a) AS A FUNCTION OF ELAPSED TIME AT 300 km ALTITUDE; IN PANEL (b) AS A FUNCTION OF ALTITUDE AT ELAPSED TIME 20 min: WESTWARD DRIFT VELOCITY: ——, ZERO; - - -, 2 km s^{-1}; · · ·, 3 km s^{-1}; ·····, 4 km s^{-1}

7) is less than that for sunspot maximum (Fig. 6). This feature is caused by the reduction in neutral molecular densities in the model thermosphere. As at sunspot maximum [Fig. 5(a)], O_2^+ plays a minor role in the molecular ion abundance [Fig. 5(b)].

Anderson *et al.* (1991) have reported ion composition results obtained from the *AE-C* MIMS instrument when the observed drift was about 2 km s^{-1} and the appropriate atmospheric conditions were those for sunspot minimum. The *AE-C* satellite was at about 270 km altitude. Results for 270 km altitude (not shown but similar to those for 300 km altitude) agree with the limited experimental data at solar minimum indicating that it is less likely that the molecular ions dominate the ion composition during the SAID, in contrast to the situation at sunspot maximum.

It is worth pointing out that, although not seen in the SAID data, the model results predict that NO^+ should constitute 5–20% of the total ion population in the topside ionosphere (Figs 6 and 7). There is evidence of increased NO^+ abundance in the topside of high-latitude troughs (Taylor *et al.*, 1975), perhaps associated with large electric fields (Rodger *et al.*, 1992). Larger molecular ion densities have been observed in the topside during major magnetic storms (e.g. Hoffman *et al.*, 1974). Also, during a major magnetic storm, Yeh and Foster (1990) have observed a large upward flux of O^+ in the topside ionosphere.

4. RELEVANCE TO EISCAT OBSERVATIONS

The calculations described above were set up specifically to model SAID events. A model of the subauroral plasmasphere has been used in which Joule heating in the *E*-region and ionization due to precipitating particles have been neglected. The effects of a vertical neutral air wind, just one of the signatures of *E*-region Joule heating, have been examined by Sellek *et al.* (1992) using the same model of the ionosphere and plasmasphere. The present model results can assist, however, in the discussion of observations of *F*-region ion heating events in addition to SAID events. We choose here to discuss observations

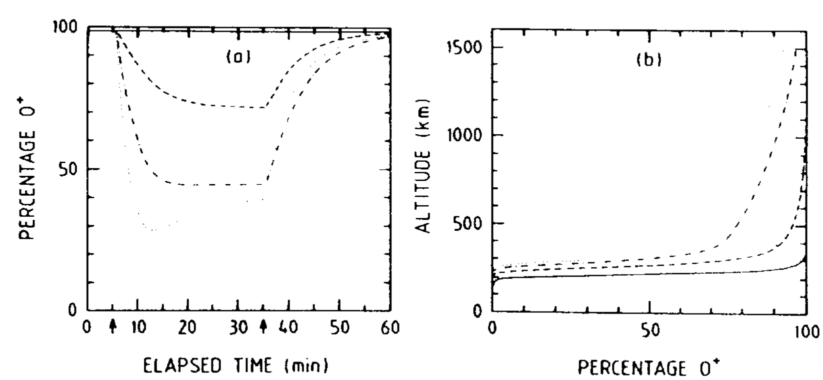

FIG. 7. AS FOR FIG. 6 EXCEPT THAT THE CONDITIONS ARE APPROPRIATE TO SOLAR MINIMUM.

of ion heating events made by using EISCAT, as recently presented by Winser *et al.* (1990) and Häggström and Collis (1990). In these studies an essential part of the interpretation of the observations is a deduction of the mean ion mass at *F*-region altitudes and so the present model results on ion composition are relevant.

Winser *et al.* (1990) have conducted a special EISCAT experiment in which the aspect angle between the radar beam and the geomagnetic field was fixed at 54.7° to avoid any ambiguity in the derived ion temperature caused by anisotropy in the ion velocity distribution function. The radar spectra were analyzed to take account also of the non-Maxwellian line-of-sight velocity distribution. Results were obtained for a night-time ion heating event. Häggström and Collis (1990) have used EISCAT common program data and have presented four case studies which included ion heating events on the dayside as well as on the nightside.

In both the Winser *et al.* (1990) and Häggström and Collis (1990) studies the initial analysis was carried out using a fixed ion composition profile. Recognizing the limitations of this assumption, a simplified form of the ion energy equation and the "best" available values of the other ionospheric parameters were used to calculate the ion temperature, T_i. This calculated value, together with the experimental value of the ratio $T_i/\bar{m}_i$, where $\bar{m}_i$ is the mean ion mass, enabled the ion composition to be deduced. For the nightside event of 16 December 1988 (Winser *et al.*, 1990) and the dayside events of 25 March 1987 and 28 July 1987 (Häggström and Collis, 1990) the composition-dependent analysis resulted in the dominance of the ion composition by molecular ions during the peak of the ion heating.

Our present model results are more directly applicable to the Winser *et al.* work than to the Häggström and Collis work, since in the model we use nightside conditions with no ionization from precipitating particles. Winser *et al.* noted that there was no strong auroral disturbance at the time of their observations. Amendments to the steady-state calculations by Winser *et al.* of the atomic/molecular ion ratio are given in a commentary by Lockwood *et al.* (1992): these lead to an increase in the calculated relative molecular abundance. The present model results (Figs 6 and 7) point to the likelihood of significant molecular ion abundances, particularly for higher drift speeds if the ion heating event has lasted (in the frame of the moving plasma) for tens of minutes.

The observations of Winser *et al.* show that the *F*-region plasma density appears, *as observed from the EISCAT location*, to recover to pre-event values. Our model results show that if EISCAT views the same volume of plasma after the event as before the event, then a return flow of O^+ from the plasmasphere (Fig. 3) can restore the *F*-region density (Fig. 4). This possibility was mentioned by Keating *et al.* (1990). An alternative possibility is that the disturbed plasma has moved out of the EISCAT field of view and that the relatively unperturbed plasma observed by EISCAT has the more usual night-time density values (see curve for undisturbed conditions in Fig. 4).

For the dayside observations re-analyzed by Häggström and Collis, the results give molecular ion abundances up to 70% (for 25 March 1987) and 90% (for 28 July 1987) in the *F*-region. If account is taken, however, of ion temperature anisotropy in the presence of large ion drifts [see Lockwood *et al.* (1992) and references therein], it is expected that the deduced molecular ion abundances will be reduced to about 15% and 35%. Since the ion drift velocities observed by Häggström and Collis are less than 2 km s^{-1}, these values are consistent with the results of Figs 6 and 7. We note that the dayside observations show the presence of significant *E*-region plasma and thus presumably significant Joule heating. This is likely to cause upwelling of the neutral air, giving rise to increased N_2 and O_2 concentrations in the *F*-region and increased rate of conversion of O^+ ions into molecular ions. Preliminary modelling of the reaction of the coupled thermosphere–ionosphere system using the UCL–Sheffield coupled model (Quegan *et al.*, 1992) has shown significant upwelling of the neutral atmosphere in response to increased electric fields.

5. CONCLUSIONS

Modelling of SAID events has been performed in which the ion drift is imposed for 30 min. This has permitted a study of the evolution of various ionospheric signatures of SAID. The relevance of the results on ion composition to EISCAT observations has also been discussed. The main conclusions are:

(1) The ion temperature in the *F*-region increases rapidly when the ion drift is imposed and is maintained at the increased value throughout the event. When the drift ceases, the ion temperature drops rapidly towards the pre-event value. At a higher altitude, such as 1000 km, the temperature increase is less and occurs more slowly; the decrease after the event requires up to an hour for the pre-event value to be re-established.

(2) There is an immediate surge in the O^+ field-aligned velocity, upwards in the topside ionosphere and downwards at 300 km altitude. After 10 min into

the event the surge in the topside disappears; at 500 km altitude, for example, a downwards velocity sets in. After the event there is a return flow of O^+ from the plasmasphere.

(3) The reductions in modelled F-region electron concentration during the event are comparable with those observed on satellite passes through SAID. The concentration behaviour depends on altitude, in accordance with the SAID observations.

(4) The relative abundance of O^+ decreases during the event; the decrease is more marked for greater values of the ion drift.

(5) The model results predict that, at a given F-region altitude, a low relative abundance of O^+ during SAID is more likely under sunspot maximum conditions, in accordance with experiment.

(6) The model results on ion composition support the deductions, made recently using a composition-dependent analysis of EISCAT data, that during ion heating events the F-region contains significant amounts of molecular ions.

(7) The model results predict significant percentages of NO^+ in the topside ionosphere.

(8) The model results may be the basis for an improved composition-dependent analysis of EISCAT data. An improvement needed in the present model is, for nightside conditions with no precipitation, to allow for ion temperature anisotropy in the ion pressure term in the field-aligned momentum equations. For dayside and/or auroral conditions, the upwelling of the neutral air suggests the need for a coupled plasmasphere–ionosphere–thermosphere model.

(9) There is a need for further details of the SAID observations to validate the suggested behaviour with time and altitude of the ionospheric and plasmaspheric signatures.

Acknowledgements—We are indebted to M. Lockwood, G. H. Millward and H. Rishbeth for useful comments. The work at the University of Sheffield is partly supported by SERC grants SGD 10269 and GRE 90571. The work at the University of Texas at Dallas is partly supported by NSF grant ATM 8813975 and NASA grants NAG5-305 and NAG5-306. The collaborative work is also aided by NATO grant 0396/88.

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